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Assessment and evaluation of PV based decentralized rural electrification: An overview

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ABSTRACT

The challenges of providing electricity to rural households are manifold. Ever increasing demand–supply gap, crumbling electricity transmission and distribution infrastructure, high cost of delivered electricity are a few of these. Use of renewable energy technologies for meeting basic energy needs of rural communities has been promoted by the Governments world over for many decades. Photovoltaic (PV) technology is one of the first among several renewable energy technologies that was adopted globally as well as in India for meeting basic electricity needs of rural areas that are not connected to the grid. This paper attempts at reviewing and analyzing PV literature pertaining to decentralized rural electrification into two main categories—(1) experiences from rural electrification and technology demonstration programmes covering barriers and challenges in marketing and dissemination; institutional and financing approaches; and productive and economic applications, (2) techno-economic aspects including system design methodologies and approaches; performance evaluation and monitoring; techno-economic comparison of various systems; and environmental implications and life cycle analysis. The paper discusses the emerging trends in its concluding remarks.

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1. Introduction

Energy is at the pivot of sustainable development of communities. It is also intrinsic to meeting the developmental needs of more than 1.2 billion people worldwide living under extreme poverty conditions. The Millennium Development Goals (MDGs) target at halving by 2015, the portion of people whose income is less than $1 a day. There are numerous other dimensions of poverty linked to deprivation, i.e. 1 billion people without access to safe drinking water. Even though energy is not included as one of the MDGs, it is widely accepted that access to clean, affordable and appropriate energy services will be a crucial factor in achieving the target of most of the MDGs [1,2]. Electricity, for instance, is an indispensable input for productive and economic activities, as well as for overall health and well-being of communities. Literature also points to the fact that the positive contribution of electricity to the Human Development Index (HDI) is strongest for first kilo-watt hour reflecting that poorest are likely to benefit from even minimum electricity inputs to meet their basic needs. The HDI values for electrified households in Bangladesh were found to be substantially higher as compared to non-electrified households in electrified villages and for households in non-electrified villages. This study also reported the overall literacy rate in the electrified households to be higher than in non-electrified households [3]. However, expanding access to electricity services is an enormous challenge for developing countries. These challenges include ever increasing demand-supply gap, crumbling electricity transmission and distribution infrastructure, high cost of delivered electricity, a variety of barriers in harnessing renewable energy resources for electricity generation [4–7]. Governments world over have been promoting the use of renewable energy technologies for meeting basic energy needs of rural communities and Government of India's efforts of the past three decades are noteworthy in this direction [8–14].

Photovoltaic (PV) technology is one of the first among several renewable energy technologies that was adopted globally as well as in India for meeting basic electricity needs of rural areas that are not connected to the grid. Even then, the 30–50% average annual global growth rate of PV is mainly driven by the markets in industrialized countries such as Spain, Germany, United States, Italy, South Korea and Japan [15]. Among various applications, grid connected distributed generation in the form of roof-top installations contribute significantly to the overall market in Japan and Germany. The US, on the other hand, has deployed systems in grid connected centralized, grid connected distributed and off-grid non-domestic (specialized applications such as in highway and pipeline lighting) sectors almost equally. Off-grid domestic sector that does not contribute much to the overall market share is in fact the most relevant sector for the developing countries in view of their energy security and energy access concerns. Within the off grid domestic sector, applications in rural areas drive the markets in these countries despite the mismatch between the cost of delivered electricity and the willingness and ability to pay by the target user group.

Literature is abound with experiences and lessons from national level projects and programmes as well as regional and global initiatives on PV. At the same time there is a rich collection of published work on the techno-economic aspects of PV. Further, the research on performance of the systems in the field and user's perception adds to understanding of the barriers related to the dissemination aspects. An indication of the richness of the literature is given by Kazmerski [16] who stated that publications in PV had risen from 3 in 1839 to 3250 in 1997. The volume of the literature, while providing insights into several technological, economical, commercial and social aspects of PV, appears to be thin when it comes to synergizing all the facets of development and learning into a comprehensive assessment and evaluation of PV for decentralized applications. This paper attempts at reviewing and analyzing PV literature pertaining to decentralized rural applications into following broad categories namely:

1. Experiences from rural electrification and technology demonstration programmes
   a. Barriers and challenges in marketing and dissemination.
   b. Institutional and financing approaches.
   c. Productive and economic applications.
2. Techno-economic aspects
   a. System design methodologies and approaches.
   b. Performance evaluation and monitoring.
   c. Techno-economic comparison of various systems.
   d. Environmental implications and life cycle analysis.

2. Experiences from rural electrification and technology demonstration programmes

As early as in 1980, the global scientific community had recognized that the PV technology was maturing, overall costs of PV were declining and commercial markets for various types of PV systems were developing. At the same time, the population growth was outpacing the expansion of the grid network, particularly to rural areas and developing countries were finding economic, financial and infrastructural difficulties in achieving complete grid based electrification. Stand alone small capacity PV systems were, hence, perceived as one of the lower cost options for rural electrification and governments in many developing countries often supported by the multilateral/bilateral funding, adopted them for this purpose. For instance, the United Nations system, in response to an increasing number of requests by developing countries, had intensified its technical assistance programs for the development and utilization of solar cells. The main areas of technical assistance had been in policy formulation, education and training, and strengthening and building institutions for research, development and application of solar energy technologies [17]. Some of the developing countries had also initiated country level programmes focusing on solar cell research and development, system design and pilot demonstration of PV applications in various sectors such as water pumping, remote meteorological stations, maritime and railway crossing, rural television and telephone equipments, seismological detection, refrigeration, low power rural industrial applications, etc. [18–29].

These systems have since been used in many projects/programmes for rural electrification with dual objectives of demonstration of the technology in order to understand key-barriers for wider dissemination as an alternate to grid extension, as well as for providing electricity to rural remote households. Some of the lessons reported in the literature have been derived from the country programmes and provide insights into system design and configurations [30,31], policies and programmes [32–38], economics and financing [39–43], institutional and financing models for dissemination [44,45], technical aspects and experiences of the users [46–54]

2.1. Barriers and challenges in marketing and dissemination

The literature has very succinctly presented challenges related to marketing, dissemination and use of PV for decentralized rural applications, while at the same time, suggesting innovative approaches for a wider dissemination of these systems. Some of the earlier World Bank/GEF/IFC projects on Solar Home System (SHS) from multi-countries highlighted that challenges could be summarized as those associated with sustainability and replicability of business models, development of regulatory mechanisms for energy subsidies and incentives, and integration of rural

electrification policy with the dissemination of SHS [33]. The literature argues that while donor-driven projects have brought about direct benefits to the users and have stimulated technology transfer and capacity building initiatives, such projects also have a tendency to distort market prices for PV systems. The Zimbabwean experience illustrates that a sustainable energy development programme requires a multi-pronged intervention that is well co-coordinated with a clear view of specific engagements beyond the donor commitment period [55]. The experience from South Pacific has attributed institutional aspects (as compared to technical ones such as inappropriate design, use of unreliable components, improper installation and poor maintenance) as main reasons for failure of PV systems. Several institutional models have been used to introduce PV systems in the Pacific, based on ownership of equipment, nature and manner of technical support, collection of fee/charges, etc. All but one (Tuvalu Solar Electricity Cooperative Society) have failed, mainly because of poor maintenance and inability to collect fee. The paper concludes that maintenance of PV systems by user is rarely successful, fee collection should be by a third party and not from the community, and spare parts and technical assistance should be readily available [56].

Taking the example of Dominican Island, Ericson and Chapman [57] have raised the negative implications of subsidizing PV market and have recommended an R&D strategy as compared to market-push strategy for developing PV markets for rural electrification in developing countries. Similarly, Jones and Thompson [58] suggest that sustainable rural electrification programs based on PV are possible by addressing financial infrastructure, capacity building, and village empowerment. Market development of PV based on product features rather than on subsidies is recommended on the basis of lessons on dissemination of PV systems in India [59]. The experience of China supports the recommendations by showing that the development of a local free market seems more successful than donor or government subsidy driven programmes for a widespread deployment of decentralized PV technologies [60]. A mix of market-based and donor-based design features in programme dissemination might be useful according to a comparative study of two projects in El Salvador [61].

Policy lessons from World Bank loan in India, Indonesia and Sri Lanka highlight that India faced a challenge of aversion to rural credit, lack of market infrastructure and lack of support to entrepreneur [62] Accordingly, availability of rural credit, transparency in grid extension, long term loan and business advisory services were recognized as stimulants for the growth of a successful PV market. Yordi et al. [63] highlighted the unavailability of skilled technicians required for promotion and installation of the systems in developing countries as a barrier, while the high costs of selling (marketing, delivery and maintenance) of SHS in developing countries has been highlighted by Posorski et al. [64], who suggested that these costs must be covered out of the product margins. Credit risk was found to be a serious concern of both financiers and dealers of PV systems and therefore credit sales of solar systems were found to be particularly challenging [65]. Similarly lack of investments and financing, high transaction costs, subsidies to conventional fuels and lack of awareness about PV systems at all levels were found to be market barriers for PV in Least Developing Countries [66]. Lack of awareness among prospective users, limited outlets for procurement, unavailability of different models catering to varying needs among various user segments, high price and limited hours of usage for solar lighting systems were some of the reasons cited for their poor dissemination in India [67,59]. Impediments cited for low penetration of SHS in Botswana are low-income status of rural inhabitants and migration of house-owners from villages to the farm land or cattle-posts [68]. While poor financial support and general lack of awareness were found to be barriers; information meetings, technical support meetings and social networks are identified as having positive effect on the adoption of PV [69].

A different perspective on the reasons for limited success of implementation of PV domestic system programs in Asia and the Pacific region has been provided in one of the recent studies [70]. This study obtained the views of those responsible for implementation SHS programmes with an aim to understand the factors that implementing agencies consider to be important in the designing and implementation of such programs. According to this study, the aims and objectives of implementation programmes are specified in very broad terms of administrative criteria, such as providing access to electricity to rural people, rather than in more specific outcomes, such as increasing users' capacities to generate income or increasing users' opportunities for studying. A lack of government policies that support project expansion as well as inadequate management capacity appears to be another significant explanation for the limited success of some programs.

Perspectives of the users and challenges faced by them have also been elaborated upon in many papers. Experiences from Mexico point at technology–user interaction being a more critical problem for adoption of PV as compared to cost, efficiency, or other purely technological issues. According to this study, the user's attitude determines the success or the failure of the program and it is important that he/she must understand the very special characteristics of PV power and play a role in operating and maintaining the system [71]. Keeping the focus on benefits to the user, the success of the GEF Solar Project has been attributed to the fact that the systems have been designed and installed according to the users' basic needs and ability to pay and the users have been involved in the dissemination process. Presence of a finance scheme has also acted as a catalyst [72]. Benefits of demonstration of PV systems for raising awareness as also facilitation of finance for the purchase of PV systems by end-users in the developing countries has also been highlighted [73]. Significance of local involvement and that of the industry at both local and global levels to stimulate best practice throughout the project cycle has been highlighted from experiences of using PV for a rural health clinic in Zambia [36]. Importance of user training and stakeholder participation has been highlighted by Yordi et al. [63] on the basis of experience with isolated rural PV systems in the European Union; by Groot [74] on the basis of experience in Africa; by Leitch et al. [75] on the basis of assessment of 45 schools project in South Africa; by Kivaisi [76] from experience of installing solar micro-grid in Zanzibar, Tanzania and by Green [77] on analysis of 15 year of solar battery charging programme in Thailand.

PV lighting or electrification can also be used to catalyze rural energy markets by stimulating demand and encouraging a culture of payment for energy services as suggested by Mulugetta et al. [55]. The PV markets can further be boosted by providing fiscal and financial incentives such as tax holiday, tax-free dividend, abolition of excise duty, etc. to industrialists and investors, as specifically studied for PV markets in Nigeria [78]. The experience of the implementation of PV in Greece emphasized the necessity for a simplified licensing procedure and a better coordination through institutions for environmental approvals [79]. Shum and Watanabe [80] have described that a successful strategy for the dissemination of PV must jointly be based upon an increasing market demand to drive cost reduction of key component such as solar cell and to capitalize upon PV systems' flexible characteristics to address unique users' requirements in downstream.

2.1.1. Summary points

- Finding a balance between market-pull (based on desired products and system designs, assessment of willingness to pay, availability of credit, after sales service network, etc.) and

donor-push strategies (in terms of R&D support, fiscal and financial incentives, simplified procedures, etc.) continues to be a challenge as both seem to have primed the decentralized PV markets across the world and continue to do so even now.

- Users' role in adoption of decentralized PV systems continues to be undermined even though there are ample studies showing the positive impacts of adequately designed and delivered user awareness and training programmes, their active participation in decision making process, and targeting specific socio-economic benefits of PV systems to them.

2.2. Institutional and financing approaches

According to Haas [81], the nineties mostly used PV systems in stand-alone decentralized mode in remote communities, while improvement in economic viability, information on wider advantages and value-added features such as environmental friendliness, improved technical performance and social acceptance led to broader market penetration in later years. The experiences gained from the earlier SHS projects (since majority of these projects and programmes used SHS) have led to many innovations and success stories in the dissemination of PV [39,82,51,83,84]. While most of the country projects/programmes were grants and donations driven and continue to be so in countries such as Mexico, Indonesia, Sri Lanka and India; free markets have developed in some other countries such as in Kenya, Zimbabwe, Bangladesh, and even in India showcasing innovations in system design as well as in financial and institutional mechanisms [85–90].

The innovations in institutional and financial models of dissemination are found from across various stakeholders namely the governments (or donors), private sector (or service providers) and users (or communities). For instance, the National Renewable Energy Laboratory (NREL) worked through a reputed NGO partner in India to provide SHS to about 300 rural households under an easy installment scheme. The NGO partner not only installed the systems, but also undertook the responsibility of monthly collections of installments that included a fee for the technician to provide after-sales-service to the users [91]. In the Comoros, a small island nation in the Indian Ocean, the ESMAP (The UNDP/ World Bank Energy Sector Management Assistance Programme) assisted the local government in developing local market for solar equipment by designing various fiscal incentives such as tax exemption, while simultaneously, launching an awareness campaign among prospective users [92]. In a specific case study of 65 stand alone projects in Catalonia, mountainous terrain in Spain, the operating costs were kept low by undertaking maintenance at three levels- inspection of operating parameters and level of electrolyte in batteries by the user, preventive maintenance, repairs and data collection by local technician and data analysis, feedback on use of energy available and maintenance management by the engineering consultant. A monthly fee of about US$ 20 on the basis of installed capacity collected from each user paid for all operation costs including repairs and insurance. However, this study indicated that a critical size of about 500 households would be required to sustain such a delivery model [93].

As an example of recent fee-for-service models, three Energy Service Companies (ESCOs) provide services to about 400 users of SHS in Zambia. The monthly fees charged by the company covers its full operating costs including the battery replacement as the ESCOs were provided with the SHS free of cost by an international donor [94,95]. Subsequently, these ESCOs are reported to be facing some financial uncertainties due to high inflation in Zambia and their inability to increase the monthly fee regularly. Despite this challenge, small ESCOs, have a strong potential to deliver an energy service throughout remote rural areas with low loads while creating jobs [96]. Specific case-studies pertaining to Energy Service Companies are also available from Bangladesh, Dominican, Honduras, Namibia, [97,45,49]. Experiences of fee-for-service model through the ESCO are also available for different systems such as a mini-grid (or a micro-utility) and solar lanterns. While the advantages cited were third party maintenance, matching of daily (or monthly) fee with user's ability and willingness to pay for the services, better service and efficient follow-up through trained technician and operators; disadvantages were overuse and misuse of systems [98–102].

The experience from Kenya have demonstrated that community-led rural micro-grids have the potential to cover a substantial proportion of the operating costs from internal revenue derived from sales of electricity and other charges. These group-based micro-grids that are initiated and managed as common property resources (CPRs) can be based on the use of a mix of energy sources (e.g., diesel, micro-hydro, solar, wind, and biomass) to serve small and geographically dispersed villages. However, to improve the prospects of rural development, the study recommends the need to develop a set of pre-qualification criteria for selecting and prioritizing rural areas and socio-economic facilities to be electrified and a better coordination of rural electrification with other infrastructure development projects [103].

In addition to SHS and centralized micro-grids, the analysis of battery-charging stations has also been presented in a few cases. A one kWp multi purpose Battery Charging Station (BCS) as a rural electrification system installed in a remote village in Vietnam provides charging facility to the batteries brought by the users and also supplies electricity to a cultural center. About forty-five families charge their batteries (20–50 Ah capacity) for lighting and black and white TV. The BCS has also provided better health services, new entertainment opportunities and has connected the isolated village to the world through a PV powered radiotelephone [104]. In a similar study, the viability of BCS from the user's as well as BCS entrepreneur (owner-cum-operator) has been presented in case of solar lantern recharging and renting business. The results indicate that the BCS is a viable business proposition for a local entrepreneur if users are willing to pay an amount of Rs. 4 per day for renting a lantern [105].

Srinivasan [106], while emphasizing the role of solar energy service companies, has highlighted that the decentralized PV market is likely to grow on the support of commercial finance from rural and other developmental banks rather than on subsidy programme. Sri Lanka's Sarvodaya Economic Enterprise Development service-SEEDs model and Grameen Shakti in Bangladesh are two well known example of extending consumer credit through micro-finance [85,107,108]. The recent example of a rural bank in India financing SHS to the user is an indication of the market moving in this direction [109]. A similar case study is from China where the free market (non-subsidy driven) has facilitated the growth of local PV industry with selling, marketing and servicing network to reach out to the rural people who can buy system customized to their needs and paying capacity [60]. SELCO-India, a SELCO International subsidiary formed in 1995 in India, utilizes the well developed network of rural development banks and financing institutions to provide access to finance to its customers while company's technicians and collection agents working on income-cum-commission basis, provide efficient after-sales-service and facilitate monthly collection of installments towards loan repayment. SELCO-Vietnam has forged a close working relationship with Vietnam Women's Union to extend consumer finance through the Vietnam Bank for Agriculture and Development [110]. Indonesia's One Million Rural Solar Home System Project is the integrated scheme for local manufacturing and technology development of the hardware and the involvement of the private sector. The project aimed at opening up a significant market for PV systems by

segmentation of consumers according to their needs and creation of special financing schemes [86]. Alzola et al. [111] present the design of an electrification kit based on the analysis of rural electrification needs wherein a relationship between electrification costs and paying capability of the communities has been established. A paper by Rao et al. [112] proposes an energy-microfinance framework that caters to the energy (lighting and cooking) needs and the corresponding financial needs to meet the capital costs of renewable energy technology of the low-income household population. The energy service company, microfinance institution, an entrepreneur and a non-profitable organization that binds all the parties together are the different entities engaged in the energy-microfinance framework. The significances of fiscal and financial incentives on reducing the effective cost of solar systems (up to 35%) to the users has been presented and discussed by Chandrasekar and Kandpal [113], while role of new financing instruments such as carbon financing has been discussed by Lee et al. [114] and Chaurey and Kandpal [115].

2.2.1. Summary points

- The funding organizations (governments and international donors), non-governmental sector, microfinance institutions, local energy enterprises and communities have contributed towards innovations in institutional and financing mechanisms for dissemination of PV systems.
- Rural electrification planning tools to map the resources with the needs and available technologies, fee-for-service delivery models involving private sector and local entrepreneurs and micro-finance aided consumer credit sales seem to be facilitating the growth of decentralized PV markets.

2.3. Productive and economic applications

Most of the reported experiences on decentralized PV systems pertain to advantages of using electricity for daily requirements, particularly those with improved illumination levels and also for productive applications [94,116–118]. Some specific case-studies have also presented unique applications where PV systems are being used for overall development of economically poor households in rural areas [119]. For instance, in Honduras, small PV systems are being used for providing power for Information and Communication Technologies (ICTs) that are enabling remote populations to have access to improved business and agriculture related services, education, health and other social requirements [120].

Experiences from Kenya and Zambia suggest that even though the direct linkages between PV based electrification and income generation appear to be limited, the use of PV has induced socio-economic development in rural areas in some important ways [95,121,103]. For instance, the use of television and radio in rural Kenya facilitates the ability of business advertisers to reach a wider audience. It has been supported by substantial evidence that television is the main driver for demand in the Kenya as well as in Zambia solar market, and PV is likewise a key component (along with lead–acid battery systems) of the micro-electricity infrastructure that supports the use of rural TV. Further, the studies suggest that even though the use of PV light by children for evening time studying is often marginalized, in some households, use of solar for education by children as well as by school teachers, links solar electrification to rural education and, by extension, to rural-to-urban migration [122]. Targeting schools serves as a possibility to improve the educational services offered in the rural setting, benefiting all students and not only those that can afford PV at home [123]. Through a detailed case study analysis of a community-based electric micro-grid in rural Kenya, it is demonstrated that access to electricity enables the use of electric equipment and tools by small and micro enterprises, resulting in significant improvement in productivity per worker (100–200% depending on the task at hand) and in a corresponding growth in income levels in the order of 20–70%, depending on the product made. Access to electricity simultaneously enables and improves the delivery of social and business services from a wide range of village-level infrastructure (e.g., schools, markets, and water pumps) while improving the productivity of agricultural activities [103].

The extent to which solar PV lighting impacts on indoor air smoke was established using the selected indicators in a paper from Ghana. The study established that solar PV lighting enables households to reduce the adverse effect of indoor air smoke and heat from kerosene lanterns. These findings call for effective links of renewable energy policies, plans and programmes to the Ghana Poverty Reduction Strategy (GPRS) and the Millennium Development Goals (MDGs). The study further suggests that financial instruments (e.g., temporary subsidies, micro-credits) should be customized, aiming at supporting low-income households to own solar PV systems to reduce indoor air smoke from kerosene lanterns [124].

Not only on the demand side, small PV businesses also offer livelihood and income opportunities at supply side. Based on the successful models of the Grameen Bank which currently provide micro-credit to rural poor individuals to purchase solar systems, an extension would be to provide larger loans to village businesses for selling, renting and servicing these systems as suggested by Biswas et al. [125]. The case-studies of ESCOs providing solar systems on lease and rent are a good example for such opportunities [87,105]. The role of rural entrepreneurship in providing decentralised energy infrastructure at the most basic level and provisioning of small PV systems to satisfy basis electricity requirements of users are highlighted by Vleuten et al. [126]. A study by Herwig [127] of the sales, jobs, and economic benefits (both direct impacts arising from product sales and indirect impacts from completing the installation of the products) has indicated that US$ 100 million of PV module sales supports over 3800 jobs.

2.3.1. Summary points

- The electricity services provided by small decentralized PV systems at domestic and village level may be small in quantum, their impact on socio-economic-cultural development of rural communities cannot be ignored.
- It would be strategically important for local government and international donors to coordinate the delivery of various developmental programmes (i.e. as education, health, community welfare) with that of PV based electrification for maximizing the impacts of both.

3. Techno-economic aspects of PV

3.1. System design methodologies and approaches

Literature dealing with system design presents methodologies and approaches for component selection and system design. A review of different methods for sizing photovoltaic systems indicates that they fall into mainly two categories, analytical methods and simulation-based schemes. An earlier study has examined analytic models based on the theory of stochastic processes that stem from analyses originally developed for analogous water reservoir, queuing and insurance risk problems [128]. A computer calculation method for determination of the elevation angle with respect to the equator for each position adopted by a quasi-static collector, the determination of the dates

for the seasonal changes in elevation, and also the calculation of the minimum collector area to be installed to meet the desired load is presented and demonstrated for three rural PV systems in Spain [129]. A method for designing the PV power system respecting the local environmental conditions is presented in the paper describing evaluation of a Palestinian project. The results of the measurements carried out over two years show the extent to which PV power generation can be matched with load demands and state of battery charge even during periods of low solar radiation [130].

A generalised methodology based on a time series simulation approach for generating a 'sizing curve' relating the generator rating and storage capacity is presented in one of the recent studies. This methodology helps in the identification of a 'design space' that explores all feasible system configurations meeting a given demand for a site. It further serves as a tool for system optimization [131]. Using this same approach, the authors have proposed a methodology for the optimum sizing of photovoltaic-battery system for remote electrification incorporating the uncertainty associated with solar insolation. The sizing curve for a given confidence level connects the combinations of the photovoltaic array ratings and the corresponding minimum battery capacities capable of meeting the specified load [132]. Similar approach of trade-off between loss-of-load or capacity shortage and levelised unit cost of electricity for SHS has been presented for different location in India using HOMER. The study suggests that different system configurations (a combination of PV module and battery capacities) can be used for different load patterns and different applications [52]. System optimization approaches using HOMER have also been found in several other studies. Techno-economic viability of hybrid photovoltaic–diesel–battery power systems for residential loads in Saudi Arabia has been presented in a paper by Shaahid and El-Amin [133]. The analysis highlights several benefits of the hybrid system. Some of these are high utilization rate of PV generation; optimal satisfaction of load; maximum diesel efficiency with minimum maintenance; reliable power supply; and a reduction in the capacities of PV, diesel and battery while matching the peak loads. Emphasis has been placed on un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions for different scenarios such as PV–diesel without storage, PV–diesel with storage, as compared to diesel-only situation. The decrease in carbon emissions by using the above hybrid system is about 24% as compared to the diesel-only scenario.

The importance of using energy efficient appliances in system design has been explained by taking the example of Compact Fluorescent Lamps (CFL) and Light Emitting Diodes (LEDs) in solar lanterns to provide clean lighting services to developing countries [134]. The advantage of intelligent charge controllers incorporating an SGS-Thompson microcontroller to improve the efficiency of the system and to protect the storage batteries with special reference to automotive batteries has been highlighted in a paper by Mashelenia and Carelseb [135]. The PV charge algorithm is also discussed. A survey of state-of-the-art charge controllers is presented by Schmela [136]. The benefit of electricity generation using solar PV located near the load has been emphasized by Kahn [137], while potential contribution to electricity supply to a remote community based on emerging technologies for embedded solar and wind renewable energy is investigated using simulation modeling by Underwood et al. [138].

A different approach for development of an integrated SHS has been presented by Krauter [83]. All components such as PV module, charge controller, inverter and wiring, support structure and foundation are integrated and pre-assembled by the manufacturer. This eases installation and reduces costs and failures. Additionally, through the integration of a water tank that serves as a cooling unit as well as the system foundation, a significant reduction of operating cell temperature was achieved, increasing electrical yield by 9–12%. Highlighting the importance of standardized approach that could be followed while formulating the off-grid electrification projects, a decision making tool has been presented which involves approaches that are to be followed for entire planning and formulation of off-grid electrification based on least cost option for 'sustainable electrification'. The paper also recommends resource mapping and GIS based rural planning models for determining the scope and best location for implementing a project [139]. On a related subject, an analysis of the implementation of photovoltaic electrification projects in traditional communities from an anthropological point of view has been discussed. The paper shows that both theoretical and practical guidance from applied anthropology are essential to guarantee successful technological change. The highlight of this paper is to aggregate the technological innovation of electricity generation to the socio-cultural change process [140].

3.1.1. Summary points

- System optimization techniques are useful for selecting ratings and types of components while designing systems for different applications.
- Standardized and integrated system design approaches are effective for implementing rural electrification projects.

3.2. Performance evaluation and monitoring

Early experience not only for developing countries, but also from developed countries has shown some light on the performance of PV systems. Evaluation results from a systematic study of the factors that determine the loss of operative state of the systems by periodic technical inspections are presented from Cuba [141]. The data analyzed on the basis of the medium frequency of failures indicated problems of technology and its social adoption. In a similar attempt to identify specific problems and difficulties experienced with PV systems and accessories installed in some Asian countries indicate that the problems are related to almost all aspects of the PV accessories as well as sizing of systems, institutional set-up and maintenance [142,143] have identified an array of factors (technical, managerial, psychological, geographical, demographic, sociocultural and economical) that influence electricity demand and consumption in SHS and hence the system design and performance. Performance degradation due to dust accumulation of PV module has also been studied [144].

System performance related aspects were gathered from an evaluation of 12 projects funded during 1993–2000 from the portfolio of the World Bank and Global Environment Facility-GEF [92]. Spread in many countries including Morocco, Lao PDR, India, Argentina and China, the evaluation indicated that customers desire a range of component options and service levels that can be provided by different capacities and sizes of systems [61,62]. This is reiterated in one of the findings of a comprehensive evaluation study of about 100 SHS projects by The Netherlands Energy Research Foundation (ECN). Accordingly, SHS dissemination can be enhanced through projects where people have a choice in system configurations as compared to projects that support only single configuration of SHS. The study also states that there is not enough information available on the performance of solar home system and projects [31,145].

System specific evaluation studies have also highlighted several usage related aspects. For instance, the evaluation of a nine year old SHS and street lighting system in Indonesia found that although the failure rate of street lighting systems was high, the villagers had a positive opinion about these systems. Further, it

was reported that technically the SHS performed well and the users were satisfied about the performance. However, in the course of time the configuration of the SHS had changed. Villagers had replaced the original strip lights with cheap locally made incandescent lamps and had replaced the initially installed 100 Ah capacity solar batteries with cheaper locally produced 70 Ah capacity car batteries [146]. In a similar study, the failure of bypass diodes in solar battery charging stations (SBCS) in Thailand has been analyzed. The inclusion of bypass diodes in these systems created an unexpected failure mode when villagers wrongly connected their batteries with reverse polarity. In a survey of 31 stations, 18 stations were disabled by burnt-out bypass diodes [147].

In contrast to the Indonesian experience, the performance of a sample of 555 lead-acid batteries taken from 2512 domestic PV lighting installed in Mexico indicated that car-type batteries (representing 87% of the sample) performed reasonably well as part of PV lighting kits [148]. However technical, environmental and socio cultural factors could negatively influence the performance of batteries in the field as shown by this survey. Accordingly, undersized storage capacity was one of the main technical factors contributing to a rapid decrease in battery performance. Improper operation and maintenance practices due to socio cultural factors and a lack of proper user training, are important recurring elements that may result in battery life shorter than anticipated, and the subsequent disappointment of the user with respect to PV rural electrification. Local availability of spare batteries at the rural community level and their proper disposal were identified as critical issues for the sustainability of large PV rural electrification projects. Desirable characteristics of an appropriate battery for PV systems, specifically for solar lanterns have been discussed by Lambert et al. [149] and Mukerjee [150].

A few more studies have highlighted component specific issues such as those linked to inverters. A project in the early eighties in France showed that users who were supplied with DC electricity through stand-alone PV systems were more satisfied as compared to those who were supplied with AC electricity through the centralized inverter due to unreliable performance of inverters [151]. This was further corroborated by Riesch [152] in the study on European rural and off-grid solar experience which found that inverters were the weakest link. Such problems have presumably not been reported in recent literature on account of technological development in inverters and other electronic and electrical balance of systems.

One of the recent studies has highlighted the impact of shading and staining on overall energy loss for single module solar home systems that are largely found in Africa and other developing countries [153]. According to this paper, the inter-panel connection topologies for very large installations are addressed to some extent by researchers world wide. However, no particular attention has been paid to the topologies of individual modules where small shading can result in an entire installation being disabled. This paper proposes that the manufacturers should re-look at current module designs since shadowing is inevitable. The importance of regular cleaning of modules to increase their efficiencies has been presented in an assessment of performance of PV system in Algeria [154].

3.2.1. Summary points

- Selection of components that are reliable and easily replaceable could have a positive impact on system performance and user satisfaction.
- System configurations to match the user requirements might improve the prospects of better acceptance of decentralized PV programmes.

3.3. Techno-economic comparison of various systems

Drennen et al. [155] had examined the economic competitiveness of PV systems in developing countries and showed that even after including externality costs, the economics of PV applications are unlikely to allow for an unsubsidized, widespread adoption of this technology in the near future without significant technological breakthroughs. The authors concluded that PV systems require sustained R&D programmes to improve PV panel and other system efficiencies. In fact, DeLucia in the year 1998 had indicated that renewables might not benefit fully from the Kyoto mechanisms because of their economics, small unit size and dispersed applications [156]. This is further corroborated by Zwaan and Rabl [157] on the basis learning curve analysis that shows that photovoltaic electricity is unlikely to play a major role either in global energy supply before 2020 mainly due to its high costs. The study however suggested that remote area applications using stand-alone systems will provide significant market volumes to further reduce the costs. Recent Africa specific studies demonstrated that global financial and technological advancements in PV are insufficient at the local African level to justify deployment of SHS in Africa [158,159]. The study concluded that the costs associated with SHS compared with conventional technologies remain quite high for very low load levels and this limited service makes the SHS a poor candidate for emissions reductions.

There are several studies dealing with comparison of levelised cost of electricity from PV with other systems for decentralized generations across various countries such as India, Brazil, South Africa, Pakistan, Bangladesh, Amazon, Malaysia, Jordan, China, Qatar, Syria, Nigeria, Korea, Malta, Egypt, Peru among others [160–172,47,78,6]. Some of the key methodologies and results are summarized here. Notton et al. [173] had highlighted the variation in PV module prices in Europe (3.5 ECU/Wp and Brazil (ECU 10.14/Wp) and its impact while calculating LCC of PV system. The study also stated that O&M varied from 1%, up to 10% of the hardware cost depending upon many factors, but suggested that 2% is a pragmatic assumption for such analyses. Other assumptions were module life time to be 20 years; battery 5 years, PCU is 10 years which are found to be valid even today. In a contemporary study from Inner Magnolia, China, the levelised energy cost was used to select the cheapest option from the most feasible options available for rural electrification. The levelised cost of PV was estimated to be 0.67–0.73 US$/kWh with manufacturer specified battery life of 3 years. It was 0.73–0.83 with actual life as found in the field to be 1 year. Diesel genset with serving continuous duty cycle equipment was estimated to be 1.09 and not serving continuous duty cycle equipment to be 0.73. Based on this analysis, the paper suggests policy measures as targets to simulate industry and provision of loan in place of subsidy [162]. An economic analysis of energy supply options (PV-diesel, wind-diesel, PV-wind-diesel and diesel only) reported by Gilau et al. [174] demonstrates that applications with high usage of renewable energy have the lowest net present cost and the same are already cost effective. However, lack of access to investment capital, limited technical capacity, limited awareness, and ineffective renewable product service and distribution systems make it difficult to implement such cost-effective projects.

Experiences from Qatar have compared gas turbine with PV and shown that even at 0.121US$/kWh for PV, it is more expensive than gas which is at 0.053 and therefore discourages the use of PV [175]. Similarly, Tanzanian example has shown that diesel is less expensive than PV if CFL or tube-lights are used as they consume less electricity. However, if incandescent bulbs are used, then PV is cheaper [84]. Malaysian experience indicates that on Life Cycle Cost (LCC) basis, PV diesel hybrid will be least cost if module prices fall from US$ 3.5 to 2.9/Wp [176]. The case of Brazil shows that for

typical village size 40–80 households, each having 1200 Whr average daily consumption totaling to about 45 kWh/day, hybrid with no back up is the cheapest option. In Pakistan, solar was found to be more competitive than wind at 20 cents per kWh against 77 for wind [177] and in Egypt, it is found to be competitive with diesel at 0.4US$/kWh [166]. An Indian study identified niche areas where renewable energy based decentralized generation options can be financially more attractive as compared to grid extension for providing electricity. PV and small wind electricity generators were found to be more attractive for providing electricity for lighting and powering televisions and transistor radios to small villages with household's population of about 20 or less in remote and inaccessible areas [178]. Another study [179] looks at a methodology for evaluation of distributed generation as an alternative path to rural electrification in Bhutan.

Studies are also available on techno-economic comparison of stand-alone SHS systems with centralized PV power plants or microgrids as well as with grid extension [180–185,163,76, 87,168,88,111,79,103,139,102,133]. One of the earlier studies has compared roof-mounted highly decentralized PV electric power systems with centralized village energy centre for typical energy requirements in an Indian village and has shown that the latter is financially superior as compared to the former on account of economic viability of the two systems. Further, the study also indicates a number of other benefits such as better maintenance; superior load management; improved security etc. that are associated with the centralized village energy centre [30]. Advantages of microgrids over SHS in terms of enhanced electrical performance and reduction of storage needs are also supported by [186]. However, the study also cautions that cost-effective measures have to be compared with additional cost features such as cost of distribution network and interconnections required for setting up microgrids.

Similar results are shown by Dakkak et al. [187] who have compared stand alone systems vs centralized systems and have found the advantages in terms of increased rate of charging of batteries, high overall efficiency and low costs of systems. The importance of analyzing energy consumption and power flows at households and village level, and socio-cultural aspects while opting for SHS or microgrids has been highlighted in a Brazilian study taking the specific examples of island and mountainous communities. The study proposes a decision support tool on the basis of life cycle costs of the two systems and emphasizes the need to establish a system regulation for microgrids similar to that of SHS [188]. Contrary to the above findings, a GTZ project in Senegal indicates that SHS might be more economical for small village energy needs as compared to village power plants citing the high cost of rural distribution network [189]. SHS are also reportedly preferred over microgrids by communities on account of independence in operational and management aspects irrespective of village size or load [93]. Romanian experience also favours SHS on account of the explicit definition of the ownership status for each individual case of SHS owner which results in increased responsibility of each user family. Also, SHS permits each user to adjust his electric current consumption to the electricity offered in accordance with the meteorological conditions. Further, SHS eliminate additional costs for construction and installation which would be necessary in the case of centralized systems. The experience of some African countries (Tunis) has shown that with centralized systems, it is necessary to have a guard at night to prevent possible theft or vandalism [117].

India has had a decade old experience of centralized village based microgrids and there are papers available on their techno-economic evaluation. Chakrabarty and Chakrabarty [182] have examined, from a broad-based socio-economic and environmental point of view, the feasibility of decentralized PV minigrids as a source of power compared to that from conventional sources in a remotely located island. A recent study presents the performance analysis of PV minigrids installed at Sagardeep Island in West Bengal state of India. The technical and commercial parameters are used to carry out the performance analysis. With the demand not exceeding 20–25 kW at a load factor less than 30%, PV offers a competitive edge as compared to conventional grid based electricity. Well-established technology, simple operation and maintenance, downward trend of cost, optimum resource availability in remote and island areas, environmental sustainability, good management systems, etc., are indications of large scale installations of PV minigrids in near future at Sagardeep Island. The paper also highlights that the fee for service payment model is effective, and there is less abuse by consumers when meters are used instead of a flat fee per connection [102].

3.3.1. Summary points

- PV systems are compared on the life cycle cost basis with many other types of decentralized as well as centralized systems for rural electrification to understand their economic competitiveness. However, results depend upon local costs of components and therefore vary across regions and countries, making it difficult to generalize them.
- Despite the above, such studies and comparative analyses help in selecting the optimum technological solution for rural electricity supply in any given situation.

3.4. Environmental implications and life cycle analysis

While providing basic electricity services to the remote rural populations, PV systems facilitate sustainable development by making a contribution to climate protection. For example, the direct benefits of SHS by displacing kerosene are reported to be as high as 15.2–21.3 litres/month in Argentina, to 12.0 litres/month in Burkina Faso and 5.0 litres/month in Bolivia. It is also reported that over 70% of the SHS have an annual emission reduction potential in excess of 200 kg CO_2 [190–192,64]. Research work has been carried out for estimation of carbon mitigation potential of renewable energy technologies, including PV in India [193]. One such study assesses the breakeven value for a PV pump to be a no regret option for CO_2 mitigation in the cases of diesel substitution and in the case of electricity substitution [194]. Purohit and Michaelowa [195] have analyzed the diffusion potential of PV pumps in India and have indicated a large potential of CO_2 mitigation by their use for irrigation pumping.

A macro-level assessment to estimate the CO_2 emissions' mitigation potential of SHS under CDM in India indicate the annual CER potential of SHS could theoretically reach 23 million tonnes. However, under more realistic assumptions about diffusion of PV technologies based on past experiences with the government-run programmes, annual CER volumes by 2012 could reach 0.5–1.4 million and by 2020, 4–9 million [196]. Chaurey and Kandpal [115] have pointed out that with carbon price of US\$10/tCO_2, about 19% cost reduction can be expected if all the benefits are accrued to the user upfront, while the benefits would reduce to 9% if carbon values are earned annually and their present worth is considered.

Apart from estimating the CO_2 mitigation potential of individual PV systems, literature presents several studies on energy pay back time and life cycle analysis of PV technologies. A paper by Stoppato [197] presents LCA of electricity generation by PV panels considering mass and energy flows over the whole production process starting from silica extraction to the final panel assembling, using the most advanced and consolidate technologies for polycrystalline silicon panel production. Briefly, the most important results of the analysis are the calculation of a gross

energy requirement (GER) of 1494 MJ/panel (0.65 m^2 surface) and of a global warming potential (GWP) of 80 kg of equivalent CO_2/panel. The energy pay back time (EPBT) has been estimated to be shorter than the panel operation life even in the worst geographic conditions. The results of the LCA support the idea that the photovoltaic electric production is advantageous for the environment. Raugei and Frankl [198] in their LCA analysis indicate that the foreseeable technological advancements in current and emerging PV technologies over the next few decades are likely to lead to significantly lower per-kWh impact than the one that characterizes the current state of the art of the PV sector. The EPBT analyses of the PV system with reference to a fuel oil-fired steam turbine and their GHG emissions and costs revealed that GHG emission from electricity generation from the PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant. From the life cycle energy use and GHG emission perspectives, the PV system is a good choice for power generation. However, it also indicates that large-scale exploitation of PV could lead to other types of undesirable environmental impacts in terms of material availability and waste disposal [199].

Fthenakis and Kim [200] determined the greenhouse gas emissions due to materials and energy flows throughout all stages of the life of commercial technologies for solar-electric- and nuclear power generation. Their analysis is based on the material and energy inventories (2004–2005) for solar technologies gathered from 12 PV companies in the Europe and the United States. The study showed that GHG emissions in the life cycles of solar electric and nuclear-fuel technologies vary, depending on the efficiencies of upstream energy, local conditions, and other assumptions. However the study predicted 40–50% lower GHG emissions in the crystalline-Si PV cycle. Another study has made extensive efforts to collect life cycle inventory data that represents the current status of production technology for crystalline silicon modules from 11 PV companies in Europe and USA. The new data covers all processes from silicon feedstock production to cell and module manufacturing as well as all commercial wafer technologies i.e. multi- and monocrystalline wafers and ribbon technology. The results of the life cycle assessment using this data report energy payback times of 1.7–2.7 years for South-European locations, while life cycle CO_2 emission is in the range of 30–45 g/kWh [201]. Yet another analysis provides the potential burdens to the environment, which include—during the construction, the installation and the demolition phases, as well as especially in the case of the central solar technologies—noise and visual intrusion, greenhouse gas emissions, water and soil pollution, energy consumption, labour accidents, impact on archaeological sites or on sensitive ecosystems, negative and positive socio-economic effects [202].

The EPBT concept however is rendered obsolete by Richards and Watt [203] who have examined other energy indicators and have suggested that the Energy Yield Ratio (EYR) be used as a new norm for PV as it incorporates the system lifetime. An energy product with an EYR of greater than unity is immediately recognizable as being able to generate more energy over its lifetime than was required to fabricate it, while a system with an EYR of less than unity can be regarded as environmentally unsustainable.

3.4.1. Summary points

- Even with modest kerosene savings at household level, decentralised PV systems contribute to GHG mitigation.
- With continuous advancements in the use of materials and production processes and techniques, the environmental implications of the life cycle of PV systems is likely to improve.

4. Emerging trends

Decentralized PV systems for rural electrification continue to hold relevance at local levels on account of the key challenges of ensuring energy security to all communities, as well as at the global level on account of climate change concerns and meeting the MDGs including education, health, environment protection and livelihood generation. On the basis of the above literature search and the global trends, there appear to be new paradigms within which decentralized PV systems seem to be finding newer markets. These are:

- augmenting the electricity supply in electrified villages for achieving better healthcare, education and community services by providing dedicated PV systems.
- providing dedicated power to livelihood activities such as computer kiosks, small shops and skill-development centres, etc. for boosting the local economy.
- improving household electrification level in electrified villages where households are scattered and grid extension is not very feasible.
- managing the periods of low demand such as street lights, compound lighting in the night in institutions/campuses where large diesel gensets run for daytime peak loads.
- pre-electrifying villages which are likely to be electrified in near future for introducing basic electricity services initially and subsequently facilitating load growth for making grid extension viable in future.
- providing portable lighting and other related electricity services for temporary sites created for excavation, construction and other works.
- augmenting the electricity based battery charging for domestic battery-inverter power back-up units in semi-rural and peri-urban areas.

In addition to the above market drivers, there are a few emerging trends in related technologies which are expected to fuel the growth of decentralized PV systems:

(a) Emerging lighting and storage technologies

The advancements in LED technology are expected to bring down their costs in terms of Rs. per Watt and give more lumen output per Watt thereby bringing down the cost of useful energy from LED based lighting devices [204]. This will eventually help in reducing the size of storage battery as well as that of the PV module in PV lighting systems which will help in their overall cost reduction. This trend will not only increase the economic competitiveness of PV lighting systems as compared to the alternatives, but would also help in enhancing their reliability by the use of state-of-the art components.

The advancements in battery technology will propel the economic competitiveness as well as the reliability even further. For instance, Ni-MH batteries have not only improved their volumetric energy densities and their useful life, the costs have also come down substantially over the past few years making them an attractive option for portable solar lanterns in view of offering longer operating hours. Some other types of batteries such as Lithium-ion are also being used in solar lanterns. Since Li-ion and Ni-MH batteries are routinely used in products such as portable computers, cordless appliances, telecommunication and medical equipment, the outcomes of technological advancements and cost reductions will benefit solar lanterns also.

(b) Distributed generation and smart mini-grids

The markets for renewable energy in India have mainly comprised of grid-connected large scale power generation units or small size off-grid systems. The emerging trend is in the form of distributed generation based smart grids (or mini-grids as their subsets) which refers to a variety of small modular power generating technologies that can be combined with intelligent (or smart) energy management and storage systems with an aim to improve the operations of the electricity delivery systems at or near the end user. These systems may or may not be connected to the electric grid. Apart from generation technologies, a smart mini-grid uses the advanced sensing, communication and control technologies to store, manage and distribute energy effectively to meet a diverse set of loads in an optimised manner.

The size of a distributed generating system may range from less than a kilowatt to a few megawatts, and it can employ a range of technological options based on renewable and non-renewable energy resources. Biomass gasifiers, solar photovoltaic systems, wind-electric generators are some of the commonly used distributed generating systems for rural electricity supply and distribution. Of several distributed generation technologies, small-scale (kWp range) roof-top PV systems are most commonly deployed in urban areas in developed countries. These roof-top PV systems are exceedingly becoming popular in developing countries including in India where a mention of these is made in the recently released National Solar Mission [205]. In Indian context, PV based distributed generation; including roof-top PV systems has tremendous potential in rural and semi-urban areas where availability of roof-space in houses as well in institutions is not a constraint. National schemes such as DDG component of RGGVY[2] and Tail-end grid connected solar power plants could utilize these systems.

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